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Vulnerability Assessment of Selected Charges Involving Heterogeneous Configurations of JA2 Sticks and Ball Powder

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Several propellant charges using heterogeneous configurations of JA2 sticks and ball powder were evaluated with respect to their response to a shaped charge jet direct impact. Vulnerability tests were performed on the JA2 and ball powder propellants separately and together. The test results show that the JA2+ball powder configurations gave a response no better than the JA2 alone. Separate tests of loose and compressed powder showed that the compressed sample gave a 37% increased response over the loose sample.

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1. BACKGROUND

In 1988, a novel propulsion concept based on geometric configurations was suggested by Olin Corporation. This propulsion concept is designed to replace the propellant in the M829 family of rounds (120 mm). The objective is to facilitate the loading of the propellant into the round without degradation in performance or in vulnerability. (At that time, the configuration of the XM829E2 used a charge that was composed only of JA2 stick propellant. To maximize the energy available in the fixed chamber volume, these sticks were cut to the appropriate shapes that accommodate the projectile boom. These operations made the propellant loading operation lengthy and, therefore, costly.)

Three propulsion configurations are proposed. They are:

(1) Annular cylinders of compacted ball propellant with JA2 sticks filling the central cylindrical channel.

(2) The same annular cylinders as in (1) with loose ball propellant filling the central channel.

(3) Bundles of JA2 stick propellant with loose ball propellant used to fill the voids between the sticks.

Aside from the obvious requirement that each propulsion system yield satisfactory ballistic performances, a major concern in this study is to ensure that the vulnerability of the rounds is no worse than that of the current rounds.

The geometric configurations require that the testing be performed on configurations close to those of the actual rounds rather than on the individual propellant components. For the vulnerability screening, it was decided to use the impulse pendulum test (Watson, Serrano, and Pilarski 1991) in which a shaped charge jet is fired directly into a simulated round and relative responses are compared. The loading configuration of this simulated round is nearly identical to that of the ballistic round. However, the variety of propellant grain sizes and formulations (deterrent concentration and gradient) and available resources made it impossible to test all the possible combinations of propellants. Thus, the interior ballistic tests were used as the initial screening of the Olin propellant combinations. Only the ballistically acceptable configurations were assessed for vulnerability response with the impulse pendulum test.

In addition, shock velocity tests were performed on the loose ball powder samples and compared to the JA2 (granular) response to obtain an idea of how close the response of the loose ball might be to that of the JA2 sticks. The shock velocity test is not designed to accommodate stick propellant.

Furthermore, because of the variety of sizes and amounts of deterrent in the loose ball powder that was already manufactured, this appeared to be a convenient way to obtain some measure of the influence of web, grain diameter, and deterrent types upon vulnerability response.

2. VULNERABILITY TESTING

2.1 Shock Velocity Tests. The shock velocity test has been described by both Watson (1986) and Heimerl (1990). The following is a brief reminder of the experimental setup. Figure 1 shows a schematic of the test setup.

For this test, the propellant is bulk-loaded into a square, wooden box. This box is then placed on a wooden stand. Above the box an 81-mm precision shaped charge is installed in such a way that the jet centerline is vertical and hits the propellant bed at the center of the square. The jet is conditioned by a piece of armor plate (1-inch RHA).

The test consists primarily of recording the propagation of the reaction wave through the propellant bed after the shaped charge jet impact. This is achieved by placing sacrificial microphones in the median plane of the bed at various distances from the jet axis. These microphones deliver a signal at the time of arrival of the wave. Time vs. distance plots provide the basic data in this experiment. Figure 2 shows a schematic of the disposition of the microphones in the propellant bed. Lyman (1991) has recently investigated the shortcomings of this technique. He concludes that for mildly responding propellants, the above procedure is adequate to provide relative rankings.

2.1.1 Approach. Four parameters were thought to have a possible influence on the vulnerability of the propellants. These parameters can be ranked in order of supposed importance as follows: 1) web (or grain thickness); 2) grain diameter; 3) deterrent concentration; and 4) deterrent gradient (expressed by the maximum pressure recorded during gun firings: a lower gradient results in a lower maximum

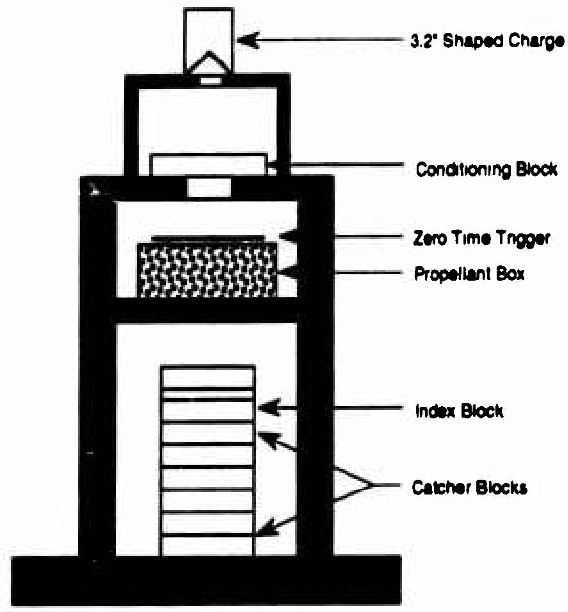
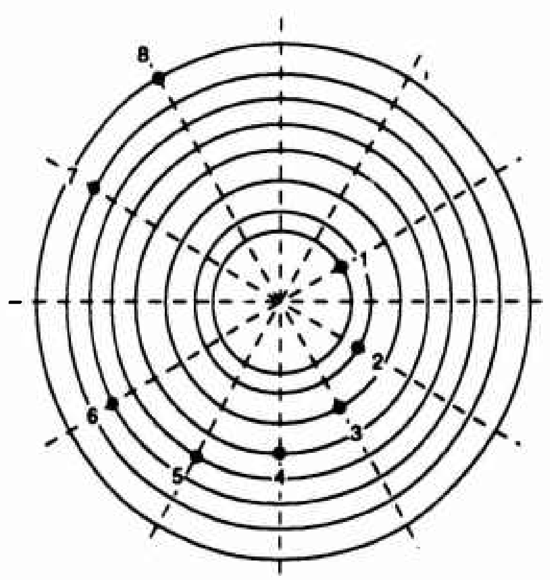


Figure 1. Schematic of shock velocity test setup.



MIC#	DIS. (mm)	(°)
1	28	30
2	36	330
3	48	300
4	60	270
5	70	240
6	80	210
7	90	150
8	102	120

Figure 2. Schematic of the microphone disposition in the propellant bed for the shock velocity test.

pressure). Table 1 gives the values of these parameters for each of the Olin loose ball propellant variations available for the shock velocity tests.

The approach originally envisioned for these tests consisted of a parametric study intended to isolate the influence of each of these parameters. A test matrix was designed and was to be used for the data analysis. However, as can be seen below, this proved unnecessary and this approach is described for the record in the Appendix.

2.1.2 Results. One shock velocity firing was performed for each of the seven propellant lots listed in Table 1. Instrumentation problems prevented the recording of data for the C (X4368) lot. It was not believed necessary to fire more than one shot per propellant because it is thought that the lack of repeatability of the results that is sometimes observed might be caused by density variations in the propellant bed. Such variations are likely to be important in a typical cylindrical or hexagonal granular propellant beds but should be very small in these ball propellant beds. These beds are much more homogeneous because of the spherical shape and the small diameter of the propellant.

The raw data consists of the electrical signals generated by a sacrificial microphone placed at a known distance from the centerline of a shaped charge jet. Eight of these microphones, placed at different locations, give the arrival time of the wave traveling through the propellant bed. These points are fitted by a curve whose general expression is:

$$d = at + bt^{0.5} + c. \tag{1}$$

This expression is differentiated to obtain the velocity. The velocity-distance points are, in turn, fitted by a curve whose general expression is:

$$v = A + Bd^{0.5} + Cd^{-0.25}. \tag{2}$$

Finally, velocity, v, is plotted against distance, d, for each propellant from Equation 2.

The results for all the propellants tested in this series are summarized in Figure 3, which presents the velocity-distance curves obtained for the six propellants for which data were recorded. Two sets of curves

Table 1. Characteristics of Loose Ball Powder Samples

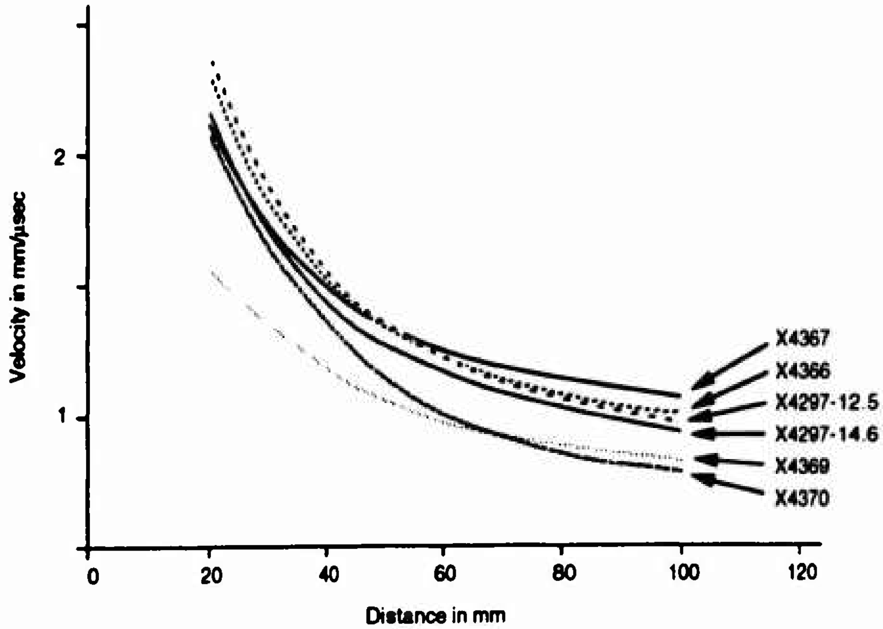
Sample No.	Code	Web (in)	Diameter (in)	Deterrent Concentration	Maximum Pressure* (psi)
X4366	A	0.082	0.115	5.8	28,000
X4367	B	0.082	0.115	5.4	35,000
X4368	C	0.086	0.115	5.2	37,500
X4369	D	0.084	0.098	6.1	23,000
X4370	E	0.081	0.098	5.9	38,000
X4297-12.5	F	0.070	0.100	6.4	33,000
X4297-14.6	G	0.065	0.100	6.2	29,500

*Measured by Olin Corporation in an instrumented 40-mm gun with a 610-g charge weight and a 2.27-kg projectile.

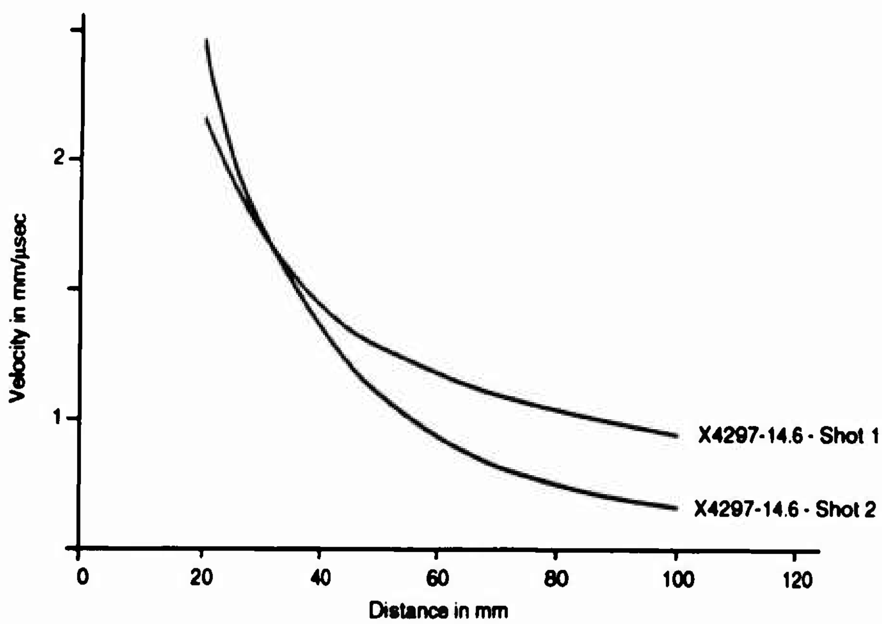
are presented in Figure 3. The first set (Figure 3a) consists of one velocity-distance curve for each sample tested. The second set (Figure 3b) presents the curves obtained for two firings with the same sample, namely, G (X4297-14.6). Figure 3b shows an acceptable reproducibility of the results. It can also be seen that the differences observed between samples on Figure 3a are within the range of reproducibility exhibited by Figure 3b. It can then be concluded that all the ball powder samples tested gave about the same response. For this reason, the more detailed test plan as outlined in the Appendix could not be followed.

Figure 4 presents a comparison of the response obtained with these ball propellants with that obtained with inert propellant and with a granular JA2 propellant. One curve was drawn to represent the ball powder sample results.

As can be seen from Figure 4, the response of the ball propellants is very mild, lying lower than the inert propellant results. This is probably due to the fact that the propellant geometries are very different. It would be of interest to fire a shaped charge jet through a bed of inert propellant having approximately the same geometry as the ball propellant, but such propellant is not available at this time. It can be concluded that the response levels of the ball propellants in this test are nearly identical for these samples and are very low.



a. Curves for the various samples tested.



b. Reproducibility test for the sample X4297-14.6.

Figure 3. Velocity-distance curves for the loose ball powder samples in the shock velocity test.

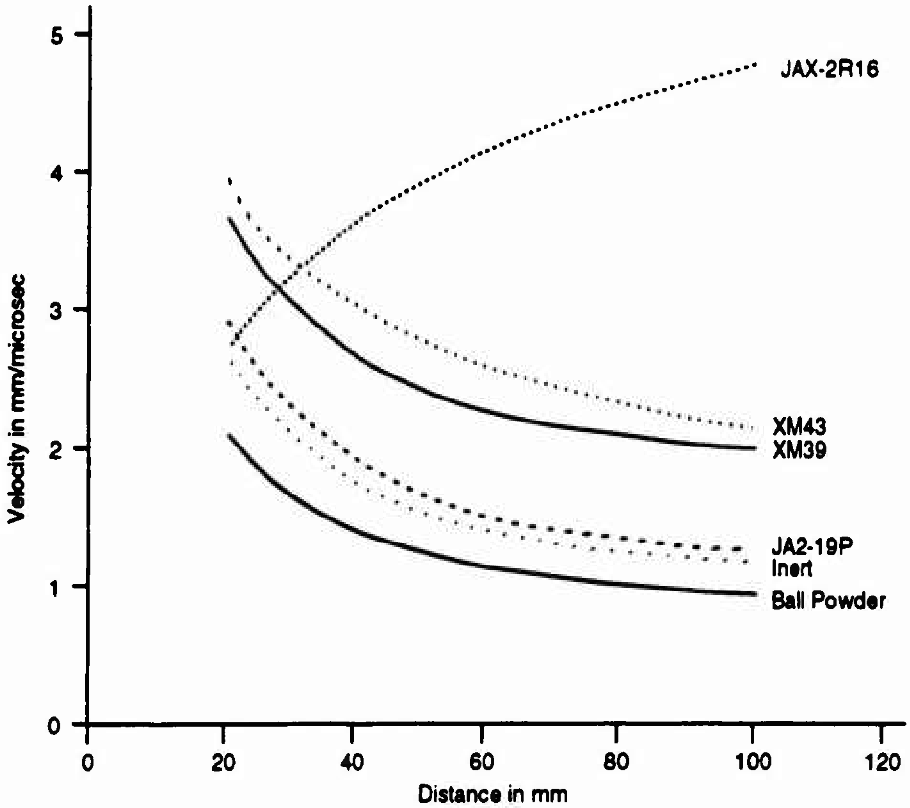


Figure 4. Velocity-distance curves for various propellants in the shock velocity test.

2.2 Impulse Pendulum Tests.

2.2.1 Test Description. For this test, the propelling charge is loaded into a 15.9-cm-diameter by 52.1-cm-length cardboard cylinder. This cylinder, filled with the test charge, is placed with the axis horizontal and parallel to the pendulum face, at a distance of 30.5 cm from the center of the cylinder to the pendulum face (Figure 5). The pendulum itself consists of a massive (3,200 kg) weight that swings freely on virtually frictionless bearings around an axis parallel to that of the cylindrical charge (Watson et al. 1991).

A bare Viper shaped charge is placed at two cone diameters (12.7 cm) from the surface of the cylinder and aimed at the center of mass of the propellant within the cylinder. The aiming angle of 63° from the horizontal simply assures that the residual jet will miss the pendulum.

The horizontal displacement and the period of the pendulum are measured directly. The impulse generated by the reaction is then calculated from the following formula:

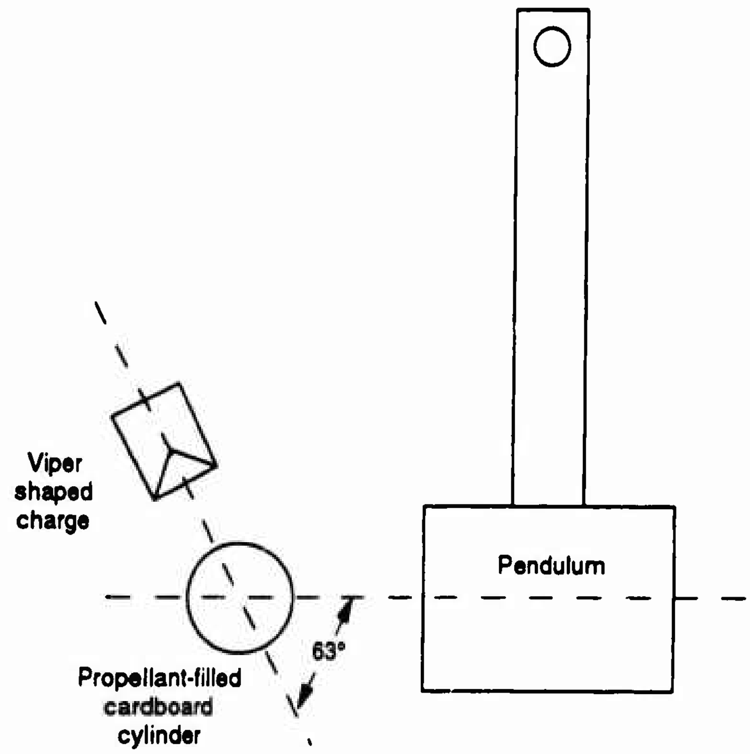


Figure 5. Schematic of the impulse pendulum test.

$$\text{Impulse} = \frac{2\pi \times \text{Mass} \times \text{Displacement}}{\text{Period}}$$

The contribution of the shaped charge itself was determined during a previous series of firings (not included here) by shooting it into a cylinder filled with sand. This contribution is subtracted from the calculated impulse to obtain the impulse due to the propellant alone. The units of impulse are Newton-second (N-s).

2.2.2 Propellant Selection. A series of impulse pendulum tests was conducted; however, unlike the shock velocity test, the impulse pendulum test permits stick as well as ball and granular propellant charge configuration. Since limited resources did not allow every possible combination of propellants to be tested, it was necessary to select a small number of configurations.

This selection was based on the results of the interior ballistic firings performed at BRL's Range 18 (Ruth 1988). Gun firings were made with the 45 different round configurations and propellant types. Out of all the combinations that were fired, only the following were found to give acceptable ballistic performance:

- compacted ball powder [10.5 lb of lot X4299 + 5.5 lb of lot X4362] + 5.5 lb of JA2 sticks
- loose ball powder [10.5 lb of lot X4297-14.6] + 11 lb of JA2 sticks.

These ballistically acceptable lots correspond to configurations 1 and 3 mentioned earlier.

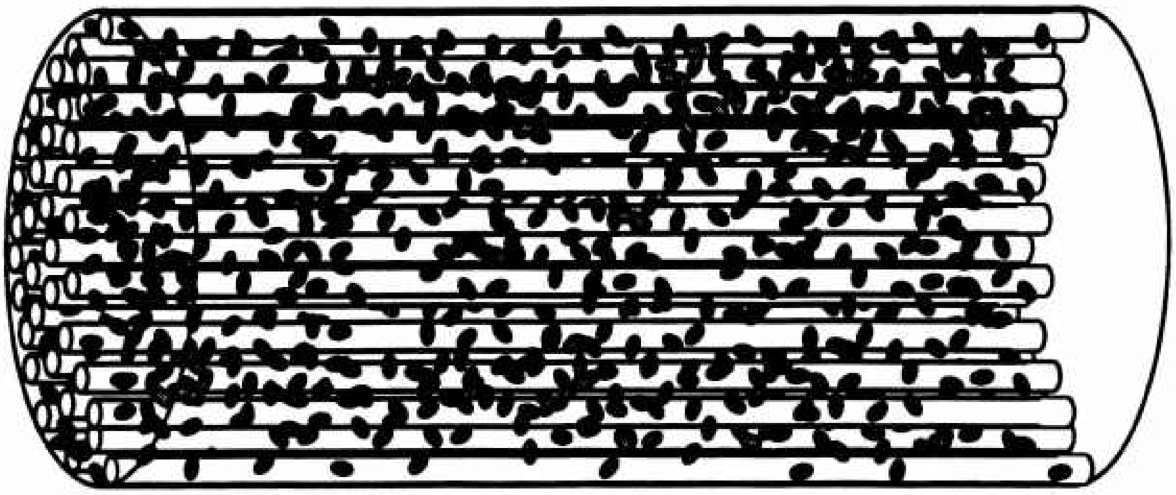
2.2.3 Impulse Pendulum Testing. The two configurations selected were loaded into 6-in cardboard tubes for impulse pendulum testing. It was originally intended to simulate the 120-mm round as closely as possible. This meant that the propelling charge would have been loaded into the tube with a simulated projectile boom. In order to achieve this simulation, wooden booms having roughly the same external dimensions as the projectile boom were fabricated.

However, these booms proved to make the loading operation especially difficult and it was decided to load the cardboard tubes without the presence of the wooden boom. This solution was chosen in order to ease the loading operation, but it was also found to exhibit an additional advantage. The test results from this series ought to be compared with those obtained from JA2 alone (this is the standard), and JA2 has been fired in the impulse pendulum test without any wooden boom in the cardboard tube. Thus, the simpler loading conditions make direct comparisons possible.

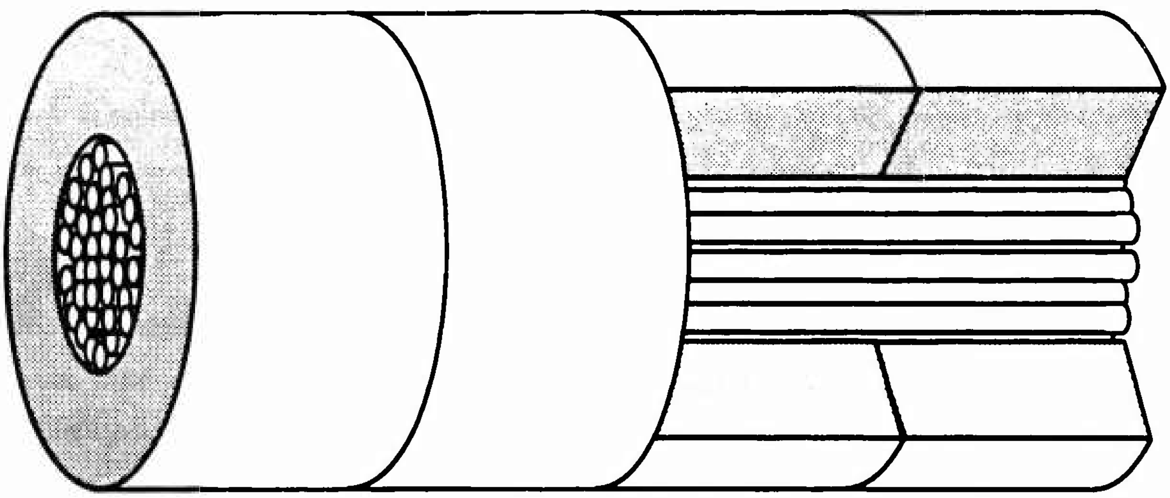
Schematics of the loading configurations are presented in Figure 6a for the configuration involving JA2 sticks in combination with loose ball powder, and in Figure 6b for the one including the annular cylinders of compacted ball powder and the JA2 sticks.

Three firings were performed in each configuration. In addition, and in order to obtain information about the response of the ball powder itself, two more tubes were loaded with 100% loose ball powder—one with the lot used in combination with JA2, namely, X4297-14.6 (G), the other with a lower nitroguanidine (NG) ball powder, X4368 (C). It was also decided to test one round loaded with the combination of 16-lb compacted ball powder and of 5.5-lb loose ball powder.

The test data are presented in Table 2. Because of the important differences in the simulated propelling charges, there are large variations in the total amount of energy that is present in the test from



a. Stick propellant and loose ball powder.



b. Stick propellant and ball powder compacted into annular rings.

Figure 6. Loading configurations for the impulse pendulum test.

one configuration to another. The values of the total impetus for each configuration are also included in Table 2. These values were calculated from BLAKE code results given by Olin Corporation (Raines 1988) for each lot tested; the value shown for JA2 was computed from a value of 1.15 MJ/kg. Figure 7 shows the test results in a graphic form. This figure includes the impulse pendulum data from shot 88-28, performed in an earlier series on JA2 alone with a similar charge weight.

Table 2. Impulse Pendulum Test Results

Propellant Configuration	Shot No.	Total Impetus (MJ)	Impulse (N-s)
JA2 stick + loose ball	88-45	23.80	1,748
	88-46		1,694
	88-47		1,748
JA2 + compacted ball	88-48	23.29	1,103
	88-49		1,031
	88-50		1,153
loose ball + compacted ball	88-51	22.79	1,045
low NG loose ball, G	88-52	22.15	889
100% loose ball, C	88-53	22.79	760
JA2 sticks (standard)	88-28	25.30	1,201

Three test results (88-45 through 88-47) give an average of 1,730 ±25 N-s and three test results (88-48 through 88-50) give an average of 1,096 ±50 N-s. Thus, we infer that even the single-shot test data of Table 2 can be compared with a high level of confidence.

For vulnerability evaluation purposes, the reference standard is JA2 and the following discussion is centered around comparisons with JA2 test data.

The most striking observation is the large (>600 N-s) increase in impulse when going from [JA2 + compacted ball powder] (1,096 ± 50 N-s; tests 88-48 to 88-50) to [JA2 + loose ball] (1,730 ± 25 N-s; tests 88-45 to 88-47). This increase is not expected when the responses of individual components are examined (tests 88-28, 88-51 to 88-53). This effect suggests a difference in the mechanism (i.e., the detailed physical processes) operant in the two test series.

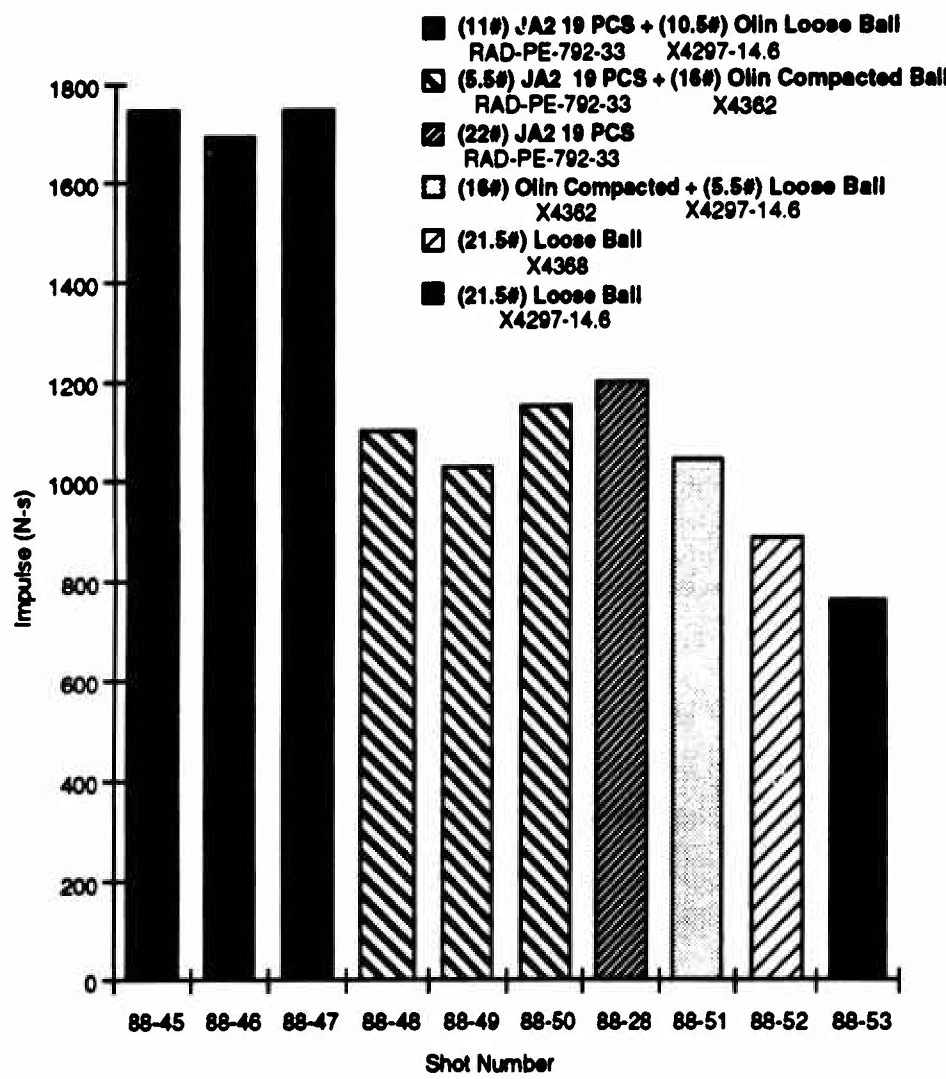


Figure 7. Measured impulse for various propellants and propellant combinations.

Table 2 shows the impetus of each configuration, calculated by adding the values for each component of the charge. They range from 22.15 to 25.30 MJ, and so a check was made to determine whether the response of the impulse pendulum test correlates with the amount of energy in the propelling charge. Figure 8 shows the measured impulse plotted against the calculated impetus of the charge tested. The values used to compute the impetus for the tested charge are (Raines 1988):

X4297-14.6	1.06 MJ/kg
X4368	1.03 MJ/kg
X4362	1.06 MJ/kg

One might expect that the level of response would tend to increase with the amount of energy in the charge; however, no such correlation was found. The charge composed exclusively of JA2 sticks has a total impetus of 25.3 MJ and that of [JA2 + loose ball powder] is 23.80 MJ; however, the corresponding impulse pendulum results are 1,200 N-s and 1,700 N-s, respectively. In addition, the [compacted ball + loose ball] combination has about the same impetus as the loose ball, yet the impulse pendulum responses are 1,045 N-s and 760 N-s, respectively. The total impetus available in the propellant charge is not the only factor driving the impulse pendulum response.

The value of the impulse measured for the combination [JA2 + loose ball powder] can be compared with the values measured for the components of this combination. The loose ball powder used in this combination was lot X4297-14.6. The result of the impulse pendulum test lot alone (shot 88-53, Table 2) measured 760 N-s, which is lower than the value of 1,200 N-s measured for JA2 stick by itself. Thus, each of the components, JA2 stick (△) and loose ball powder (■), give impulse pendulum responses that are each less than the combination [JA2 + loose ball powder](▲) (see Figure 8).

It is generally assumed that energy losses in the propellant bed occur at the gas/solid interface and that the solid/solid interface is the main contributor to the propagation of the reaction. If this is true, the propellant bed with fewer intergranular voids (i.e, higher packing density) produces the greater response. This provides a possible explanation for the result that the combination [JA2 + loose ball powder] gives a more violent response than each of its components.

However, it must also be noted that the configuration consisting of the compacted annular cylinders and JA2 exhibits a response level that is very close to that of JA2 alone (or loose ball powder alone for

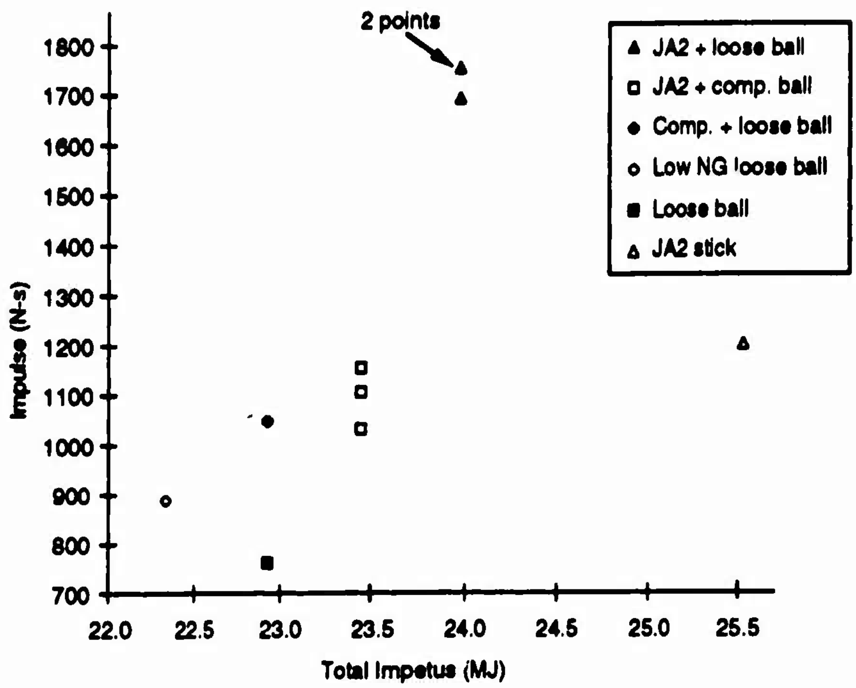


Figure 8. Measured impulse vs. total charge impetus.

that matter). This might be due to the fact that JA2 and the ball powder are well separated in such a charge configuration and, therefore, do not behave as a continuous solid but as individual components with well defined interfaces. The configuration used in the impulse pendulum test for the combination of JA2 and loose ball powder is not quite the configuration of a ballistic round. The ballistic round would be loaded in such a manner that the stick propellant is located near the cartridge wall and the ball powder in the space left vacant around the projectile boom in the center of the case. Such a loading configuration would allow a better separation of the components of the charge and might give a different level of response in the impulse pendulum test.

In Figure 7, we compare the results of shots 88-51 and 88-53. The latter is the response of 21.5 lb of lot X4297-14.6, while the former is the combination, 16-lb compacted ball + 5.5-lb loose ball (lot X4297-14.6). Since the loose ball lot is the same in both cases and the total energy is about the same, we conclude that the consolidation is responsible for the observed 37% increase in vulnerability response.

3. CONCLUSIONS

When tested by themselves, all the samples of ball powder that were produced by Olin Corporation exhibit a low level of response in the shock velocity test and the impulse pendulum test. However, when used in combination with JA2 stick propellant, as is the intended application round, the response level varies greatly and is dependent upon the loading configuration.

When annular cylinders of compacted ball powder are used in combination with JA2 sticks (Figure 6b), the impulse pendulum results are about the same as when each component is tested alone. This result is consistent with the fact that this configuration tends to keep the two types of propellants physically separated.

For the combination of JA2 stick and loose ball powder (Figure 6a), the response level of the mixture is much greater than that of either component tested separately. Apparently, the loading arrangement of Figure 6a contributes to this observed high response. This hypothesis, that the loading configuration can alter the response, is supported by the observed increase in responses of the compacted vs. the loose ball (see shots 88–51 and 88–53 of Figure 7). Further investigation of this phenomenon would seem to be important as it may give rise to a better understanding of the overall jet-propellant bed interaction phenomena.

In conclusion, the use of loose ball propellant with JA2 stick propellant should be avoided until the exact nature of its interaction with a shaped charge jet can be understood and techniques for ameliorating its effect are developed.

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APPENDIX:

PARAMETRIC STUDY TO ISOLATE THE INFLUENCES OF PROPELLANT VULNERABILITY PARAMETERS

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As mentioned previously, four parameters were thought to have a potentially significant influence on the behavior of the ball powder samples. These parameters are: 1) web, 2) grain diameter, 3) deterrent concentration, and 4) deterrent gradient. A plan to determine which of these parameters is the most important for the vulnerability response of the propellant was devised and is presented below.

Ideally, shock velocity results would be compared for two propellants that differ only by a single parameter. For example, propellants with the same web, the same deterrent concentration, and the same deterrent gradient, but with significantly different grain diameters, would provide information on the relative influence of the latter parameter. In practice, because we were working with propellant that had already been manufactured, some judgment had to be exerted to determine what "same" was.

The a priori matrix of propellants whose shock velocity results were to be compared with each other is shown in Table A-1. In this table, the propellants are identified by the codes given in Table 1, for clarity.

Table A-1. Comparison Matrix for the Ball Powder Samples

Parameter of Interest	Propellant Pair	Differences in the Considered Parameter				Remarks
		Web (in)	Diameter (in)	Deter. conc. (%)	Deter. grad (kpsi)	
Web	E & G	0.011	0.002	0.5	5	Note 1
	D & G	0.019	0.002	0.1	6.5	
Diameter	A & D	0.002	0.017	0.3	5	
	B & E	0.001	0.017	0.5	3	
Deterrent Concentration	A & B	0.000	0.000	0.4	7	Note 2
	A & C	0.004	0.000	0.6	9.5	Note 3
Deterrent Gradient	D & E	0.003	0.000	0.2	15	

Note 1: If it were shown that the deterrent concentration does not have a major influence on the outcome of this vulnerability test, then the pair E & F could be used to determine the effects of web variations.

Note 2: This pair exhibits differences both in deterrent concentration and in deterrent gradient and therefore does not provide a unique means of comparison. Moreover, the difference in deterrent concentration is about the same as that which is assumed to be negligible for the study of the influence of the diameter. Nonetheless it was selected because any of the other pairs gives even larger differences.

Note 3: The pair A & C should be an excellent indicator of the influence of the deterrent concentration if the comparison between pair D & E (X4369 and X4370) shows that the deterrent gradient has little influence.

Because all propellants tested gave about the same response in the shock velocity tests, the comparison matrix shown in Table A-1 could not be implemented.

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